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TECHNICAL REPORT

Measurement of mass flow of water in the stems of herbaceous plants

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Abstract. Heat balance methods of stem flow measurement offer the opportunity to measure directly the mass flow rate of water in plants. We have tested one such approach; the constant power heat balance method of Sakuratani (1981). The results supported his statement of an approximate accuracy of 10% when measuring the transpiration rate of herbaceous plants. The response to sudden changes in stem flow rate is not instantaneous, but investigation of the time constant shows that it decreases as stem flow increases, to the extent that, at flow rates typical of daytime conditions the system is capable of accurately tracking changes in stem flow within 5 min or less.

We describe a new gauge design that is relatively rugged, simple to use with an appropriate digital datalogger and suitable for field use over prolonged periods of time. It does not injure or penetrate the stem, is amenable to continuous and direct recording of the mass flow rate of water in the stem and requires no calibration. A further refinement, which should improve both the accuracy and the dynamic response of the system, is proposed.

Key-words: sap flow, stem flow, transpiration measurement, heat balance.

Introduction

Direct, accurate, non-invasive, and continuous measurement of stem flow in herbaceous plants has been an elusive goal of physiologists and agronomists for many years. Most work has been based on heat pulse techniques, wherein the xylem flow velocity is obtained from the time required for a discrete heat input to travel from its source to a sensor further up the stem. This method appears to have been proposed first by Huber (1932), and has been analysed, implemented and tested by a number of workers, both for use on herbaceous plants (Bloodworth, 1956; Wendt, Brooks & Runkles, 1965) and on trees (Swanson, 1972; Lassoie, Scott & Fritschen, 1977). Marshall (1958) and Swanson & Whitfield (1981) have provided mathematical analysis, the latter showing that correction for the interruption of flow caused by the inserted heater eliminates the need for empirical adjustments previously used to convert apparent heat pulse velocity to sap velocity. Cohen, Fuchs & Green (1981) have also reported refinements in instrumentation and calibration to improve the accuracy of the method.

A fundamentally different approach to stem flow measurement is based on a heat balance, rather than a heat pulse velocity. It can be traced to Vieweg & Ziegler (1960), variations having been developed by Daum (1967), Sadler & Pitman (1970) and Cermak, Deml & Penka (1972). In general, the mass flow rate of water in the stem is obtained by balancing the fluxes of heat into, and out of, a stem segment. A recent example is the work by Cermak, Kucera & Penka (1976) designed for use in trees. In which the heat input to a segment of the trunk is automatically and continuously adjusted, so as to maintain a constant temperature difference between the heated segment and the unheated trunk below. As stem flow changes, the required heat input must also change, to provide the basis for stem flow measurement. Being a null method, it is sensitive to small changes in flow rate, with an essentially instantaneous time response. Schulze *et al.* (1985) showed that this method, without requiring calibration, gave accurate results. However, the electronics required for compensation are not simple and must be provided separately for each gauge.

An alternative, for application to herbaceous plants, is the constant heating method recently implemented and evaluated by Sakuratani (1981, 1984). In this method, the heat input from an external annular heater is kept constant and fluxes of heat out of the system are calculated from measured temperature gradients, enabling direct calculation of the mass flow rate of water in the stem. We report here on tests of the method, modifications in the Sakuratani design, and an examination of the dynamic response of the system.

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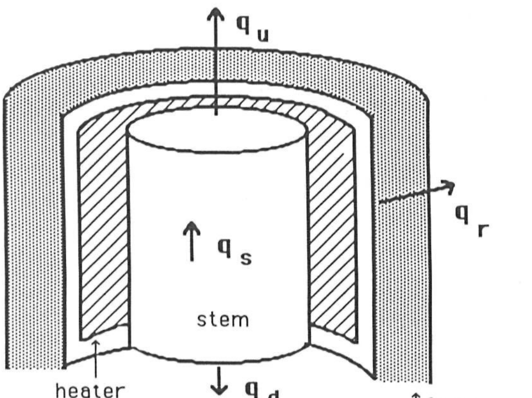

Figure 1. Heat balance of the heated stem segment. In studies of cotton and sunflower, the length of the heater was 10 mm, and stem diameters ranged between 8 and 18 mm. The thickness of the insulation is 12 mm and its length is 50 mm. Symbols refer to eqns 1 and 2, q_s is the rate of heat transport by the sap stream.

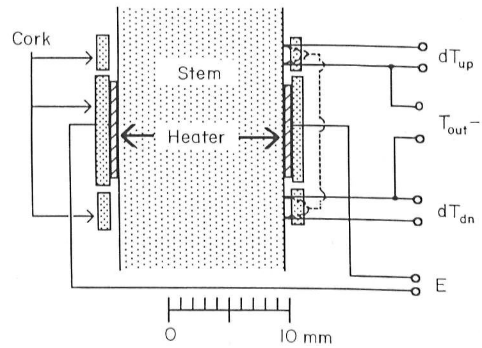

Figure 2. Vertical cross-section of a stem with a gauge in place. The outer insulating foam sheath is not shown. The heater extends around the entire stem, as do the high-density cork strips, which are 2 mm thick. The thickness of the heater is 0.2 mm. The distance between the thermojunctions in each pair is 3 mm.

Materials and methods

Theory

The heat balance approach as proposed by Sakuratani (1984), can be described with reference to Fig. 1. A flexible heater encircles the stem and provides a small, steady and known amount of heat. Insulation, with a thermal conductivity much lower than that of plant tissue, encloses the heated segment and extends for several centimetres both above and below it. In the steady-state, the continuous heat input must be balanced by the heat flow out of the system, the system being composed of the heated stem segment and the heater. The outward heat flow can be partitioned into conductive fluxes up and down the stem, radial conduction into the insulation and mass heat transport by the sap stream, whatever its direction and however distributed over the cross-section.

Figure 2 illustrates how each of the heat fluxes is measured. The conductive flux of heat upwards (q_u) can be calculated with Fourier's Law for a one-dimensional heat flow (Eqn (1)).

$$q_u = k_{st}A(\mathrm{d}T/\mathrm{d}X), \qquad \mathrm{W} \qquad (1)$$

where k_{st} = the thermal conductivity of the stem tissue (W/(m · K)), A = the cross-sectional area of the stem (m^2), and $\mathrm{d}T/\mathrm{d}X$ = the temperature gradient (K/m). The derivative in eqn (1) is approximated as the output from two differentially wired thermojunctions which were 3 mm apart and in direct contact with the stem, the lower of the two being immediately above the heater. This presumes, as was done by Sakuratani (1981), that owing to the radial and vertical extent of the insulating jacket, the gradient of temperature was uniform over the cross-section. Another pair of thermojunctions located similarly below the heater allowed the determination of the conductive flux downward. In eqn (1), the value of A must be known from an actual measurement, and that of k_{st} is taken to be 0.54 W/m · K, a value which is the average of measured values reported for various herbaceous spp. (Sakuratani, 1984), and is slightly less than that of water.

The radial outward flow of heat is calculated from the voltage output of a thermopile composed of eight thermojunctions in series, located on either side of a 2-mm cork sheath between the heater and the foam insulation. The flux is approximated by eqn (2), the integrated form of the equation for radial heat flow (q_r) in a cylinder of infinite length (Carslaw & Jaeger, 1959):

$$q_r = 2\pi k_{co}L(T_i - T_o)/\ln(r_i/r_o), \qquad \mathrm{W} \qquad (2)$$

where k_{co} = the thermal conductivity of cork (W/m · K), L = the length of the heated segment (m), T_i = the temperature at the inner surface of the sheath (K), T_o = the temperature at the outer surface of the sheath (K), r_i = the radius of the inner surface of the sheath (m), and r_o = the radius of the outer surface of the sheath (m). All parameters in eqn (2) are constant for a given configuration, and can be combined with the conversion factor relating the thermopile output (E) to the temperature difference ($T_i - T_o$), into a single sheath 'conductance', K_{sh}, with the units of W/V$_o$ (the subscript signifying voltage output from the thermopile), so that eqn (2) may be rewritten as:

$$q_r = K_{sh}E. \qquad \mathrm{W} \qquad (3)$$

Subtraction of the three fluxes (up, down, out) from the known heat input gives the heat transported by the sap stream. To calculate the mass flow rate of water from the sap heat transport, it is necessary to know the temperature difference between the water entering and leaving the heated portion of the stem. To obtain this value, the upper thermojunction nearest the heater is differentially wired to the lower junction nearest the heater. Again, the assumption of radial thermal homogeneity is made. This temperature difference, multiplied by the heat capacity of water, is divided into the sap heat transport, yielding the mass flow rate of the sap itself.

$$F = (P - q_u - q_d - q_r)/(C_p \times (T_{out} - T_{in})), \qquad (4)$$

where F = the sap flow rate (g/s), P = the power input to heater (W), C_p = the heat capacity of the xylem sap (J/(g·K)), T_{out} = the temperature of the junction above the heater (K), and T_{in} = the temperature of the junction below the heater (K).

The value of k_{sh}, required in eqn (3), is calculated from eqn (4), by setting F equal to zero and making measurements on a stem that has been excised and sealed with vaseline, to ensure that the sap flow rate is zero. This procedure is a zero set, not to be confused with a calibration or measurement of the response to known changes in sap flow rate. In this sense (and in contrast with most transient techniques), the method is absolute.

Gauge design

We tested four gauges, provided by Sakuratani and fabricated as described by him (1984). Our testing procedure, described later, showed each gauge to be accurate to within $\pm 10\%$, but two problems were encountered. First, the manganin wire used to make the heaters was susceptible to corrosion. In continued use, three of the heaters lost continuity, a problem Sakuratani (personal communication) had also noted. The second problem was the fragility of the thermojunctions, which tended to break loose from their backing or to pull away from direct contact with the stem, particularly during the process of installing or removing the exterior foam insulation sheath. We modified the design to eliminate these difficulties, and built and tested the new gauges.

Figure 3 shows an exploded view of the redesigned gauge, unwrapped and spread out flat. The commercially manufactured heater (Fantech Corp., Cerriros CA 90701, U.S.A.) is etched from 0.25 mm Inconel foil on 0.05 mm Kapton, and is coated with varnish. So far it has resisted corrosion over weeks of continuous use, and is thinner and more flexible than the manganin coil previously used. The heaters used had resistances of approximately 160 Ω.

The upper and lower thermojunctions were made with 0.127 mm copper and constantan wire. Holes for the wires were drilled through each of the two high-density cork annuli with a 0.2-mm drill bit, using a template to give an accurate spacing of 3 mm. Wires were threaded through the holes, after which the junctions were either welded or soldered. After the junctions had been made they were affixed to the cork backing with isocyanurate glue.

A separate cork annulus encircled the heater. A thermopile consisting of eight soldered junctions, four glued to each side of the cork, was made with the 0.127-mm copper and constantan wire located on the circle that divided the annulus equally, as shown in Fig. 3. The insulating sheath was made from standard polyurethane foam pipe insulation of 12-mm wall thickness. It was split longitudinally and folded open. Then the cork backing strips containing the thermojunctions and heater were placed inside and secured with flexible silicone adhesive, to make insulation an integral component of the gauge, in contrast to the Sakuratani design.

The wire leads from the thermojunctions and the heater were terminated by a seven pin connector that was then fastened to the outside of the sheath. Finally, Velcro straps were attached to the outside of the foam sheath so that the gauge could be firmly clamped on a stem, ensuring good contact between the latter and the thermojunctions.

Results and discussion

Testing

A number of gauges were fabricated in the manner described and tested on cotton and sunflower plants growing in pots. In each case, the value of K_{sh}, the sheath 'conductance', had been previously determined, as described above, using excised stem sections of the same diameter as the intact test plants. The values of K_{sh} ranged from 400 to 800 W/V$_o$, depending upon the gauge diameter, which varied from 8 to 18 mm.

In the tests, the surface of each pot was covered to

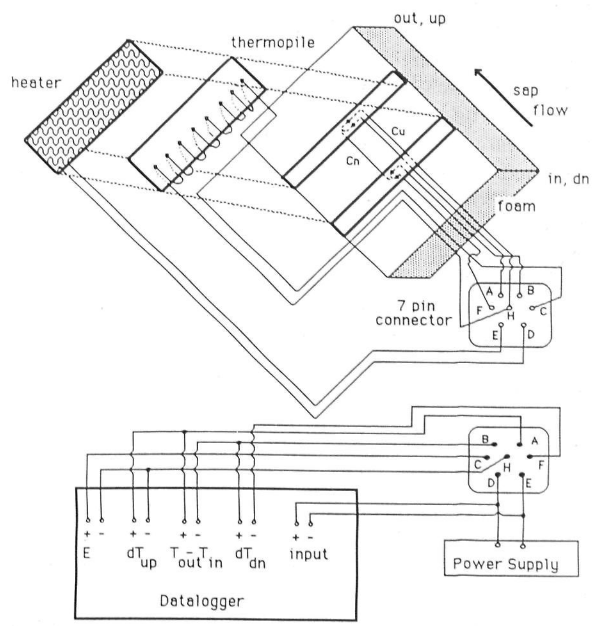

Figure 3. Exploded view of an unwrapped stem gauge. The upper and lower thermojunctions are stitched into the cork strips. The thermojunctions of the thermopile are connected by loops around the bottom edge of the central cork strip, or annulus. Each gauge requires five input channels of the datalogger.

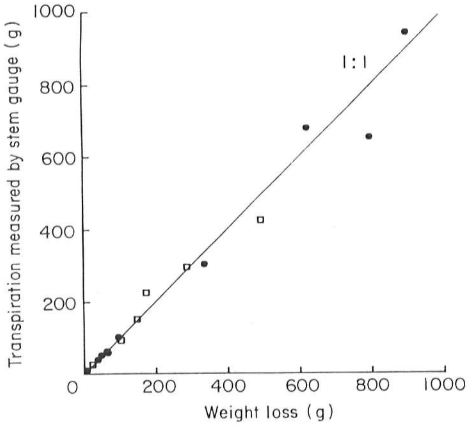

Figure 4. Comparison of transpiration measured with stem gauges against transiration measured as weight loss. These tests were conducted in a controlled environment chamber, with either cotton or sunflower plants, over time periods ranging from 2 to 24 h. Air temperature was 29 ± 1 °C, and the wet bulb temperature was 24 ± 1 °C. Different levels of evaporative demand were generated by changing the irradiance, provided with a bank of high-pressure sodium lamps, over a range of 50–400 W/m².

reduce soil evapouration, and transpiration losses were measured directly with a 10 kg electronic balance, with a sensitivity of 0.1 g. The power to the heaters was provided with a DC power supply (model 6200B, Hewlett–Packard), set at 4 V $\pm 0.01\%$ to provide the desired power input, the latter being approximately 0.1 W. As the input voltage was monitored continuously, it did not need to be absolutely constant, only steady. The gauge signals, which were in the 1–100 μV range, were measured every 15 s with a data collector of adequate resolution (CR7; Campbell Scientific Inc., Logan, Utah, U.S.A.). The latter was programed to compute the sap flow rate in real time, using the equations given earlier. The cumulative flow, obtained by summing the product of the rates and the duration of the scanning interval, was compared to the observed weight loss to determine the accuracy of the method. Figure 4 shows the results of a series of such tests, performed with several gauges, under a variety of evaporative demands. These results confirm the conclusions of Sakuratani (1984), who established the relative accuracy of the method to be approximately 10%.

Dynamic response

The method requires the establishment of a steady-state, so there is a lag in the response of the gauge to a sudden change in stem flow, due to the thermal inertia of the stem. The time constant for such a system was given by Kucera, Cermak & Penka (1977) as:

$$t_c = (m_s \times C_{p,s})/(Q \times C_{p,w} + L_s), \quad (5)$$

where t_c = a time constant (s), m_s = the mass of the

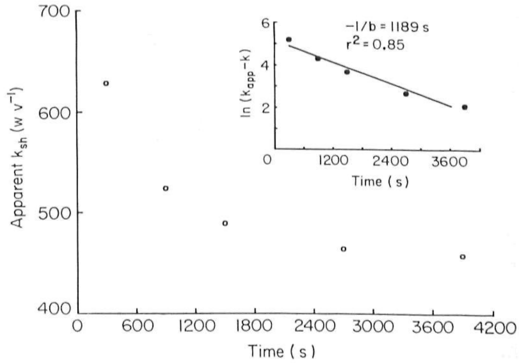

Figure 5. Determination of the time constant under no-flow conditions. The gauge was placed on a detached stem, and the recorded signals were used to calculate the apparent sheath conductance (using eqn 4) from the time power was initially turned on until a steady value was reached.

heated segment (kg), $C_{p,s}$ = the heat capacity of the segment (J/(kg · K)), Q = the stem flow rate (kg/s), $C_{p,w}$ = the heat capacity of xylem sap (J/(kg · K)), and L_s = the thermal conductance of the system (W/K). The last quantity is the rate of heat loss at zero sap flow rate for each degree of temperature difference between the heated segment and its environment.

It can be seen from eqn (5) that the dynamic response of the system can be improved by either reducing the size of the heated segment or increasing the thermal conductance of the system, but there are practical limitations in both cases. In particular, if the heated segment is made too small, the heat input must also be reduced to avoid physiological damage, with the result that the various outward fluxes and the corresponding signals also diminish increasing the relative error of the measurement. If the thermal conductance of the gauge is made too large, the assumption of one-dimensional conduction in the stem becomes increasingly tenuous.

Balancing these constraints, the gauges described herein were designed for use on cotton stems with a diameter of approximately 10 mm, with the length of the heated segment being 10 mm. The foam used for the insulating sheath had a thermal conductivity two orders of magnitude lower than that of stem tissue. A computer simulation showed that under such circumstances the heat flow in the stem is essentially vertical and non-divergent, substantiating the assumption of a radially uniform temperature gradient. The thermal conductance of these gauges (L_s) is approximately 0.03 W/K, meaning that the maximum temperature inside the heated segment at zero sap flow will exceed ambient temperature by 1 °C for every 0.03 W of heating. In practice, a heat input of 0.1 W was used, resulting in a maximum temperature increase of slightly greater than 3 °C.

For a given design, the time constant is a function of the stem flow rate only, eqn (5) indicating that the

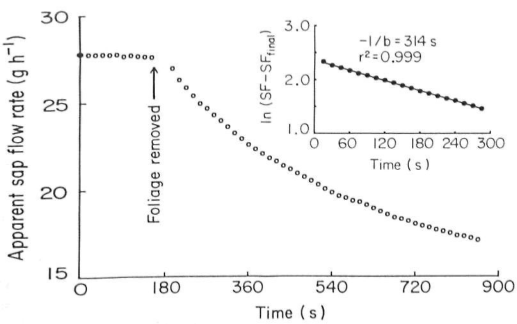

Figure 6. Determination of the time constant in the presence of flow. The upper third of a cotton plant was excised, and the apparent sap flow rate indicated by the gauge was recorded every 15 s until a new steady rate was reached. In deriving a time constant, it was assumed that the true sap flow rate decreased to the new value immediately upon excision.

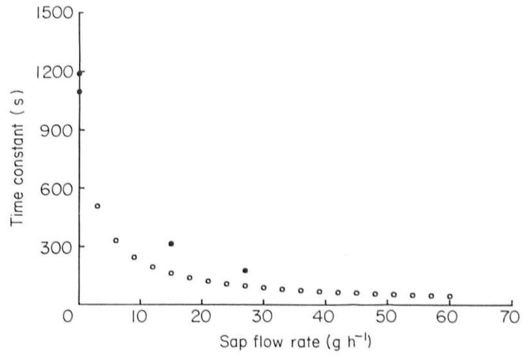

Figure 7. Time constant of the system as a function of sap flow rate for a gauge of 10 mm diameter, defined as the time required to reach 63% of the difference between initial and final output following a step change in flow rate or heat input. (●) Measured, (○) theoretical.

dynamic response of the system will improve as stem flow increases. An estimate of the time constant can be obtained by plotting the response of the system to a step change in either stem flow or heat input. Figure 5 shows the response under no-flow conditions to a change in heat input. A gauge of 10 mm internal diameter was attached to a stem severed at both ends. The output signals were used with eqn (4) to calculate an apparent sheath conductance from time zero, when the power was initially supplied to the heater, until a steady value, the true sheath conductance, was reached. If the logarithm of the difference between apparent k_{sh} and true k_{sh} is plotted against time, the slope represents the inverse of the time constant for the system at zero flow.

Similarly, Fig. 6 shows the response of the stem gauge to a step change in flow rate. This was created by rapidly removing a large portion of foliage from a plant transpiring under steady environmental conditions. This is not a true step change in flow rate, due to tissue capacitance and changes in radiant energy distribution following foliage removal, but it provides an approximate indication of gauge response. Time constant estimates derived in this way for two flow rates, as well as the no-flow estimate, are shown in Fig. 7, together with the theoretical relationship calculated with eqn (5).

It is apparent that rapid changes during periods of low sap flow will not be accurately monitored. However, under a typical daytime evaporative demand, sap flow is sufficient to reduce the time constant to 1 min or less, meaning that changes in sap flow rate can be tracked closely, within 5 min or less.

It is evident that the heat balance method, as described, could be in error when there are changes in ambient temperature that change the heat content of the stem segment, violating the steady-state assumption. This did not occur in our tests, which were conducted at constant temperature in a growth chamber, but errors can be expected in the use of the gauge outdoors in the presence of a strong diurnal temperature fluctuation. These would be, for the most part, self-compensating over periods of 24 h or longer; overestimates of stem flow during periods of rising temperatures would be offset by underestimates during periods of falling temperature.

However, in many cases it is the rates over short periods of time that are of greatest interest. To correct for the systematic errors in these calculated rates due to changes in stem heat content, and at the same time, improve the dynamic response of the system, we propose that the temperature of the stem segment be measured continuously with the upstream and downstream thermojunctions already present on the inside surface of the gauge, assuming that the temperature changes over time in the entire segment would be represented by those immediately above and below the stem. Then, the changes in the heat content of the stem segment can be computed and added into the heat balance equation.

Conclusions

The heat balance approach of Sakuratani (1984) provides a method for measuring sap flow in the stems of herbaceous plants that is sufficiently accurate to be useful in many agronomic and physiological applications. It is physiologically innocuous and it is an absolute measurement, in that no calibration is required, only a zero set. The output signals, of the order of 10 μV, are relatively noise-free, and can be measured with 1% relative precision with currently available dataloggers. Further, the calculations are sufficiently straightforward to allow real time processing of the data from several gauges by one datalogger. The dynamic response may not always be adequate, particularly during periods when stem flow is low, but this does not diminish the usefulness of the method for quantitative determination of plant water use over prolonged periods of time. Measurement of changes in the heat content of the stem segment should improve the dynamic response, at the same time correcting for deviations from the steady-state assumption.

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